

# A model for gamma-ray binaries, based on the effect of pair production feedback in shocked pulsar winds

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**Abstract.** We analyze the model of gamma-ray binaries, consisting of a massive star and a pulsar with ultrarelativistic wind. We consider radiation from energetic particles, accelerated at the pulsar wind termination shock, and feedback of this radiation on the wind through production of secondary electron-positron pairs. We show that the pair feedback limits the Lorentz factor of the pulsar wind and creates a population of very energetic pairs, whose radiation may be responsible for the observed gamma-ray signal.

**Keywords:** gamma-ray binaries, pulsar winds, radiation processes

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## INTRODUCTION

Binary systems consisting of a massive star and a compact object are known to be sources of high-energy gamma-rays. The nature of compact objects in these systems is not exactly known; there are models, which either assume they are black holes (e.g., [1]) or pulsars (e.g., [2]). In the present paper, we consider gamma-ray binaries with pulsars, where one naturally expects collision of stellar wind with ultrarelativistic pulsar wind. In all such models, the pulsar wind is assumed to be the source of observed gamma-rays – through inverse Compton scattering of stellar photons – either directly, by electrons moving with extreme bulk Lorentz factor  $\sim 10^4 \div 10^5$  (e.g., [3]), or from the wind termination shock, where electrons are accelerated well beyond their initial (bulk) Lorentz factor  $\sim \text{few} \times 10^3$  (e.g., [4]).

A system, where there is a dense radiation field (here – stellar photons) and an ultrarelativistic plasma flow (here – the pulsar wind) can launch a runaway-like particle acceleration (converter acceleration), as been already discussed in application to gamma-ray bursts and active galactic nuclei ([5, 6]). In gamma-ray binaries the feedback from downstream of the pulsar wind to its upstream is realized through two-photon pair production. Below we show that it is possible to construct a model, which can reproduce main observed properties of gamma-ray binaries without involving any physical processes apart from the two-photon pair production feedback itself and consequent cooling of the energetic pairs through synchrotron and inverse Compton radiation. Obviously, the physics

of gamma-ray binaries is much more complex than this simple model, but our model demonstrates that the pair feedback and subsequent converter acceleration has to be included as an essential, if not the most important, component in any advanced model for gamma-ray binaries with pulsar winds.

## MODEL DESCRIPTION AND PARAMETERS

For our model, we assume the following setup (base on the parameters of LS 5039 and LS I +61 303, which can be considered to be typical representatives of gamma-ray binary population). The massive star has the luminosity  $L_s = 3 \times 10^{38}$  erg/s and the mass-loss rate  $\dot{M} = 10^{-6} M_\odot/\text{yr}$ . The mass outflow is due to stellar wind with velocity  $V_w \equiv \beta_w c \simeq 0.01c$ . The pulsar orbits the massive star at the distance  $D = 3 \times 10^{12}$  cm and produces a magnetized ultrarelativistic wind with power  $L_p = 10^{36}$  erg/s, which consists of electron-positron pairs and has the Lorentz factor  $\gamma$  (we will show later that  $\gamma \sim 10^3$ ) and magnetization parameter  $\sigma \lesssim 1$ .

The pulsar wind termination shock is located at the distance  $R = \left( \frac{L_p}{\beta_w \dot{M} c^2} \right)^{1/2} D$  from the pulsar, where the dynamical pressures of the two winds are equal. At this distance, the energy density in the pulsar wind is  $w = L_p / (4\pi R^2 c)$ , what constitutes a fraction  $\epsilon_w \simeq 0.5$  of the energy density of the background thermal photons supplied by the massive star,  $w_b = L_s / (4\pi D^2 c)$ . Thus, neither comptonization of stellar radiation nor the synchrotron and self-Compton radiation is an a priori dominant emission mechanism.

The shock-bounded pulsar wind region is filled with stellar photons and the high-energy radiation produced at the termination shock, which forms (inside the shock) an isotropic and uniform photon field. Interacting with each other, these photons occasionally produce electron-positron pairs, which are picked up by the pulsar wind, becoming much more energetic, and then lose energy for radiation on their way to the shock and, to a greater extent, after crossing the shock and entering the shocked plasma. The rate of secondary pair production  $\dot{N}_{ep}$  does not depend on the angular distribution of the parent photons as soon as at least one of the interacting photon fields is isotropic (the shock-generated photons are always isotropic), and the velocities of secondary pairs are uncorrelated with the wind velocity. When pairs with such velocity distribution are picked up by the pulsar wind, their energy increases on average by the factor  $\gamma^2$ .

## PAIR FEEDBACK IN PULSAR WINDS

Energetic secondary electrons and positrons readily cool: a fraction of their energy is radiated before they reach the termination shock, the rest is radiated in the post-shock region. The cooling is more efficient in the post-shock region both because the particles spend more time there and because synchrotron emission is possible in the shocked plasma in addition to inverse Compton emission. The synchrotron emission from secondary pairs supplies additional low-energy target photons for production of new pairs, forming a feedback loop.

The overall contribution of this feedback to the radiative efficiency of the shocked pulsar wind can be estimated as

$$\eta_f = \frac{\gamma^2 \dot{N}_{ep} E_{ep}}{L_p}, \quad (1)$$

where  $E_{ep}$  is the average total energy of a secondary pair at the moment of birth. Should the pulsar wind become heavily loaded with secondary pairs, its Lorentz factor decreases to the value, which ensures the feedback efficiency  $\eta_f$  is less than unity.

Consider two isotropic populations of photons with energies around  $E_1$  and  $E_2 = 4(m_e c^2)^2/E_1$  ( $E_1 > E_2$  for definiteness), and energy densities  $w_1$  and  $w_2$ . The pair production rate approximately equals

$$\dot{N}_{ep} = \frac{4\pi}{3} R^3 \sigma_{\gamma\gamma} \frac{w_1 w_2}{E_1 E_2} c = \frac{\sigma_{\gamma\gamma}}{12\pi D c} \frac{\varepsilon_1 \varepsilon_2 \varepsilon_w^{1/2} L_s^{5/2}}{(m_e c^2)^2 L_p^{1/2}}, \quad (2)$$

where  $\sigma_{\gamma\gamma} \simeq 10^{-25} \text{ cm}^2$  is the angle-averaged pair production cross-section,  $\varepsilon_1$  and  $\varepsilon_2$  are the energy densities in two populations of interacting photons in units of the background stellar radiation energy density. With increase of  $E_1$ , the optimal energy of target photons  $E_2$  decreases and, for a given radiation energy density, the number of target photons (hence opacity) goes up. So, all other things being equal, the larger is  $E_1$  (which determines the energy of electron-positron pair at birth,  $E_{ep}$ ), the larger is the feedback efficiency.

Even though the feedback may be controlled by inverse Compton radiation of primary pairs, the overall radiated power is mainly due to secondary pairs, which have energies  $\sim \gamma^2 E_{ep}/(2m_e c^2)$  and upscatter stellar photons inefficiently because of the Klein-Nishina suppression in the scattering cross-section. Their main energy-loss channel is synchrotron radiation in the post-shock region, where secondary pairs form the cooling distribution and their synchrotron spectrum has the photon index  $-3/2$ . It extends in energy up to

$$E_s = \gamma^4 \left( \frac{E_{ep}}{2m_e c^2} \right)^2 \frac{\hbar e B}{m_e c}, \quad (3)$$

where  $B = (2\varepsilon_m \varepsilon_w L_s c)^{1/2}/(Dc)$  the magnetic field strength in the post-shock region.

When the pair feedback starts to develop, secondary pairs are born in interaction of comptonized stellar photons (produced by the primary electrons) with energy density

$$w_1 \simeq \frac{3\pi R}{ct} \frac{\gamma}{\gamma_0} w_b = 4\pi R \sigma_T \frac{\gamma^2}{\gamma_0} \frac{w_b^2}{m_e c^2}, \quad (4)$$

where  $t$  is the cooling timescale,  $\sigma_T$  the Thomson cross-section, and  $\gamma_0$  is the Lorentz factor of the pulsar wind as it would be in absence of the pair feedback. The target radiation field is synchrotron radiation of the secondary pairs. Given the photon index  $-3/2$ , its energy density at  $E_2$  is

$$w_2 = \left( \frac{E_2}{E_s} \right)^{1/2} \eta_f \varepsilon_w w_b. \quad (5)$$

Combining equations Eq. (1, 2, 3, 4, 5) we find the self-consistent Lorentz factor:

$$\gamma = \left(3\pi 2^{1/4}\right) \gamma_0 \frac{T_s^{1/2}}{\sigma_{\gamma\gamma} \sigma_T} \frac{\varepsilon_m^{1/4} L_p}{\varepsilon_w^{3/4} L_s^{11/4}} D^{3/2} m_e c^4 \left(\frac{\hbar^2 e^2}{m_e^2 c^3}\right)^{1/4}. \quad (6)$$

The feedback efficiency enters Eq. (6) inexplicitly, through the ratio  $\gamma/\gamma_0$ . With this ratio much less than unity the feedback efficiency is  $\eta_f \sim 1$ .

The Lorentz factor, found in this way, depends on the distance to the massive star,  $\gamma \propto D^{3/2}$ . Then, the synchrotron cutoff energy is very sensitive to this distance:  $E_s \propto D^{11}$ . If this volatile synchrotron cut-off approaches  $m_e c^2$ , then the pair feedback enters a different, more robust mode, where the synchrotron photons from secondary pairs get absorbed on themselves, so that the feedback becomes over-efficient and saturates, keeping  $E_s$  somewhat below  $m_e c^2$ . The self-consistent Lorentz factor now becomes

$$\gamma = \frac{2^{1/4} (m_e c^2)^{1/2}}{T_s^{1/4} (\hbar e)^{1/8}} \frac{D^{1/8}}{(2\varepsilon_m \varepsilon_w L_s c)^{1/16}}, \quad (7)$$

where we substituted  $E_s$  for  $m_e c^2$ , keeping in mind that dependence of the equilibrium Lorentz-factor  $\gamma$  on  $E_s$  is very weak. Under typical conditions, Eq. (7) gives  $\gamma \simeq 750$ .

The pair feedback model predicts that the radiation from pulsar wind and the shock region contains several spectral components of different origin. First, it is emission from (slowly cooling) primary pairs – inverse Compton from stellar radiation, peaked at

$$E_1^{\text{IC}} = 3\gamma^2 T_s \sim 5 \text{ MeV}, \quad (8)$$

and synchrotron, peaked at  $E_1^{\text{sy}} = \gamma^2 \frac{\hbar e}{m_e c} \frac{(2\varepsilon_m \varepsilon_w L_s c)^{1/2}}{D c} \sim 0.3 \text{ eV}$ , which is overwhelmed by the radiation of the massive star. Next, there is emission from secondary pairs, both synchrotron, peaked at  $E_2^{\text{sy}} \sim m_e c^2$ , and (less efficient due to the Klein-Nishina effect) inverse Compton, peaked at  $E_2^{\text{IC}} = \gamma^2 m_e c^2 \sim 0.3 \text{ TeV}$ . The energy of comptonized photons is limited by the energy of secondary pairs.

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